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A PROPOSED INTERNATIONAL TROPICAL REFERENCE ATMOSPHERE UP TO 1000 km

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ABSTRACT

Motivated by the need in many aerospace applications for a meaningful reference atmosphere characteristic of the whole of the tropics in both the northern and southern hemispheres of the globe, a proposal was made earlier by the authors for altitudes up to 80 km. This proposal is here extended up to an altitude of 1000 km. The proposal is based on balloonsonde, rocketsonde, grenade, falling sphere and satellite data in the range 0 to 100 km, and on the MSIS- 83 model from 100 to 1000 km. The proposal consists of linear segments in the temperature distribution with values in degrees Celsius of 27, -9, -74, -5,-5, -74 and -80.4 at geopotential altitudes of 0, 6, 16, 46, 51, 74 and 84.69 km (= 86 km geometric altitude) respectively, beyond which the description is in terms of geometric altitude. A linear segment between 86 and 97 km with a lapse rate of 0.6°C/km is followed by an elliptic variation commencing with a temperature gradient of zero at 97 km to reach at 110 km a temperature of -45°C with a gradient of 15°C/km. This gradient remains constant up to 120 km where the temperature is 105°C. Beyond 120 km the temperature distribution follows a Bates type of profile up to 1000 km to reach a value there of 760°C. A sea level pressure of 1010 mb and an acceleration due to gravity of 9.78852 ms^{-2} corresponding to the Tropic of Cancer are used in the preparation of the atmospheric tables.

INTRODUCTION

With the presently available meteorological data it is now possible to characterise atmospheric conditions typical of a season, month or even a day. However, a standard atmosphere representative of the mean annual conditions is still essential for many aerospace applications. An International Standard Atmosphere (ISA: see /1,2/) valid for mid-northern latitudes specified upto 32 km, and its proposed extension to higher altitudes (such as in /3/), have been formulated for meeting these needs.

The authors have previously discussed at length /4 to 7/ the problems of defining atmospheric standards for India and the tropics, and have shown that it is possible to specify a suitable Indian Standard Tropical Atmosphere (ISTA) and an International Tropical Reference Atmosphere (ITRA), valid up to 80 km and about 30°N in latitude. None of the standard or reference atmospheres formulated earlier /8 to 15/ for the tropics has covered the above latitude and altitude range. In the present work ITRA is extended to an altitude of 1000 km. The subsequent sections discuss the accuracy and consistency of the data available for use in formulating the present proposal.

DATA BASE FOR ITRA UP TO 1000 KM

The present reference atmosphere is developed in four parts, namely,

(i) in the troposphere and lower stratosphere, using balloonsonde data,

(ii) in the upper stratosphere, utilising rocketsonde data,

(iii) in the mesosphere, considering grenade, falling sphere and the Nimbus satellite data, and

(iv) in the thermosphere, based mainly on the MSIS-83 model.

Table 1 shows the details of the available data and their sources.

REMARKS ON THE QUALITY AND CONSISTENCY OF DATA

Troposphere and Stratosphere

As discussed in /7,16/ the post-1970 balloonsonde data of the India Meteorological Department as also the Monthly Climatic Data for the World /17/ for the American stations up to 20 km are consistent. Further the rocketsonde data up to about 50 km from various countries, in particular the USSR and USA which have provided the data for a large number of stations /14,18,19/ over the globe, are consistent and thus can be used for proposing the reference atmosphere. Beyond about 50 km there are unresolved differences /20,21,22/ among the above rocketsonde data, perhaps due to the exposure of the thermistor probes to the free-molecular conditions around 50 km and above.

Mesosphere

For the higher altitude range of about 50 to 100 km we have used the falling sphere and grenade data /23 to 26/. These data are generally consistent among themselves and possess an accuracy of about 2 to 3^{o}C. Smith et al /23/ report pitot data as well, but these lead to temperature values which are about 5^{o}C higher on an average from the grenade data for the low latitude stations such as Ascension & Natal (see Table 1); as the reason for this discrepancy is not clear we have not considered the pitot data. Data in this altitude range are not as extensive as one would wish but are nevertheless just adequate to propose a reasonable reference for describing the mean annual conditions. The most recent Nimbus data /27/, worked out from the radiance values, are quite consistent with the present proposal from about 50 to 70 km as shown in Figure 1. However, beyond this altitude the satellite values are higher than the falling sphere and the grenade data, and the reason for this is not yet clear.

Thermosphere

In this region, most grenade or falling sphere data are available up to about 100 km. Beyond this altitude the number of soundings is very small. Further beyond about 80 km one has to specify in any reference atmosphere the varying concentration of the various species, which have to match with the conditions that may be specified at about 120 km by a suitable thermospheric model such as in /28 to 31/. These problems are discussed in greater detail later. For the present work we have used the MSIS-83 model /30/ for the above purpose.

THE PHYSICAL CONDITION OF THE ATMOSPHERE FROM SEA LEVEL TO 1000 KM

From sea level up to an altitude of about 85-86 km, air is known to be in a thoroughly mixed condition and thus the relative concentrations of the various constituents do not change. Up to this height the atmosphere can be described in terms of the molecular scale temperature T_M, versus the geopotential altitude H. Using the relation between temperature and altitude one can work out the pressure, density and other atmospheric properties.

Beyond about 85 km molecular dissociation commences, and above 100 km molecular diffusion predominates, and so air can no longer be treated as a perfect gas. It is then necessary to specify at each level the varying concentrations of the different species constituting air. As in /3/, the description at and beyond 86 km is in terms of the kinetic temperature T, versus the geometric altitude Z. In this region the vertical density profile $n_i(Z)$ of the atmospheric constituent i as given in /3,32/ is

$$n_i(Z) = n_i(Z_o)\{T(Z_o)/T(Z)\}I(K/(D_i+K),H)I(D_i/(D_i+K),H_i)$$

$$.I(\alpha_i.d\ \ln T/dZ.D_i/(D_i+K),1)I(V_i/(D_i+K),1) \quad ...(1)$$

$$\text{where } I(x,y) = \exp\left(-\int_{Z_o}^{Z}(x/y)dZ\right) \quad ...(2)$$

and Z_o is taken to be 86 km as in /3/. The K and D are respectively the height-dependent eddy and molecular diffusion coefficients; H and H_i are the scale heights for air and each of its constituents and α_i is the species thermal diffusion coefficient. The first three integrals in Eqn(1) refer to mixing and diffusive processes. The so-called flow term denoted by the fourth integral has to account for the complex chemical and transport processes which occur in the above region of the atmosphere /33 to 35/. However, in developing a reference atmosphere that should be capable of being generated easily for comparison with experiment and be useful for analytical studies, one has to look for reasonable assumptions which simplify the approach. For this we assume that the turbopause level for the various species terminates sharply at a height of Z_{ti}. The flow term is more complicated than the mixing and diffusion terms. For this we propose a simple form such as

$$V_i/(D_i+K) = a_i\{(120-Z)(Z-86)\}^2 \quad ...(3)$$

where the a_i are adjustable parameters to be so chosen that the particular species concentration values at 120 km are close to the average values for low latitudes from the MSIS-83 model. The major constituent N_2 is assumed to be in complete diffusive equilibrium above its turbopause height. Thus once the temperature distribution is specified the N_2 number density distribution can be worked out. In fact we adjust T(Z) such that the value for the number density of nitrogen at 120 km matches as closely as possible with the value from the MSIS-83 data. Thus the value of its $a_i = 0$. The atomic oxygen is strongly governed by the chemical and transport processes, but as we shall discuss below its distribution is dealt with differently. Thus the a_i need to be chosen only for Molecular Oxygen, Argon and Helium.

Beyond an altitude of 120 km the various species constituting air are assumed to be in diffusive equilibrium. The MSIS-83 model in fact specifies the conditions of the temperature, its gradient at this altitude as also the temperature profile from 85 km up to an exospheric altitude of 1000 km for varying latitude and longitude, and solar, magnetic, seasonal, daily and hourly

conditions; this is used to extend ITRA up to 1000 km.

If the temperature distribution known as the Bates profile /36/ is written as

$$T(Z) = T_E - (T_E - T_{120}) \exp(-sz') \quad \text{...(4)}$$

where T_E, T_{120} are respectively the temperatures at 1000 km and at 120 km, with

$$z' = (Z - 120)(R_e + 120) / (R_e + Z),$$

$$s = (dT/dZ)_{Z=120} / (T_E - T_{120}),$$

and R_e = the radius of the Earth,

then the number density can be expressed in closed form /36/ as

$$n_i(Z) = n_i(120)\{T_{120}/T(Z)\}^{(1+\alpha_i+1/sH_i')}.\exp(-sz') \quad \text{...(5)}$$

with $H_i' = (R_e T_E)/(m_i g(120))$,

the argument of g(.) referring to the altitude.

PROPOSED INTERNATIONAL TROPICAL REFERENCE ATMOSPHERE (ITRA) UP TO 1000 KM

The philosophy adopted by the authors /4,5,6/ in proposing the reference has been that it should

(a) be reasonably close to mean conditions,

(b) within the range of variation inherent in the atmosphere over the space and time which it describes and the uncertainty in the data, be as simple as possible,

(c) adopt, where no physical principles are violated, as many of the parameters in the ISA as possible, and

(d) be dynamically consistent.

Temperature distribution with altitude

Usually straight line temperature distribution with altitude is used. This is done since a closed form integration for obtaining the atmospheric properties is then possible.

As indicated in /6,7/, the proposed standard has a sea level temperature of 27°C and a lapse rate of 6°C/km up to 6 km (which is lower than the ISA value but is characteristic of the humid tropics) and 6.5°C/km (as in ISA) from 6 to 16 km, the tropopause height where the temperature is -74°C. In the stratosphere, a single lapse rate of -2.3°C/km all the way up to a stratopause height of 46 km, with a temperature of -5°C, was found to fit the data very well /6/. Though this temperature is somewhat higher than indicated by the Thumba value, we consider it appropriate because of the fact that the stratopause temperature increases with increasing latitudes. The available data in the mesosphere indicate that the constant temperature stratopause extends up to 51 km. Considering the differences between the geopotential and geometric height which is of the order of about 1 km, it turns out that the above level for the end of stratopause is more appropriate than the value of 52 km in our earlier proposal /7/.

In the mesosphere it should be noted that inversions occur during some months and there are also well known double mesopauses with different temperature values as well. However the mean annual conditions can be specified in a simple way as shown in Figure 1. Due to the sparsity of the data, we have considered stations at both low and high latitudes, which indicate the latitudinal variation and thus help in formulating the present reference atmosphere for the tropics. In the present proposal a constant lapse rate of 3^{o}C/km from 51 km to 74 km leads to a temperature of -74^{o}C (as at the tropopause!). The Wallops Island and the Churchill data /23/ indicate that the latitudinal variation is weak (atleast between 50 and 85 km). Further, up to an altitude of 70 km, excellent agreement exists for the present proposal with the Nimbus data /27/ averaged over 30 S to 30 N in latitude. Also the present proposal up to about 75 km is consistent with the various monthly reference atmospheres for the northern and southern hemispheres as proposed in /14/,/15/ respectively.

Between 80 and 100 km it is once again expedient to go by the variations between low latitude and mid-latitude station data. From Figure 1 one may note that the Ascension Island data indicate some kinks but the Kwajalein data are smooth, but beyond 100 km these are based on only three soundings. The MSIS-83 model data show much higher values than the Kwajalein data around 85 km. Thus, considering the latitudinal variations between the station data of Kwajalein, Wallops and Churchill we find that it is best to have from 74 km altitude a lapse rate of 0.6^{o}C/km (geopotential) up to a geopotential altitude of 84.69 km (= 86 km geometric height) and later once again a lapse rate of 0.6^{o}C/km (geometrical) between 86 and 97 km of geometric altitude.

In the altitude from about 100 to 120 km we noticed that the MSIS - 83 data averaged over the range of magnetic index A_p = 0 to 10 and solar activity index $F_{10.7}$ = 75 to 225, is close to its value for A_p = 4.0 and $F_{10.7}$ = 150. Further the above is averaged over 30 S to 30 N. These averaged model data are also given in Table 1. In the present proposal the temperature variation has been chosen close to such latitudinally averaged MSIS data which leads to a value for the number density of nitrogen close to MSIS - 83 value at 120 km. Thus the minimum temperature in the present proposal in the mesosphere is -80.4^{o}C at 97 km and the subsequent rise in the temperature in the lower thermosphere is described by an elliptical distribution which has a temperature of -45^{o}C at 110 km where the gradient reaches the value 15^{o}C/km. Subsequently the temperature increases at the same rate up to 120 km where it reaches a value of 105^{o}C. Figure 2 shows ITRA between 0 and 120 km. A similar procedure indicates a choice of 760^{o}C (=1033.15^{o}K) at 1000 km.

Distribution of nitrogen

This is obvious as explained in the previous section since the temperature distribution from about 74 km up to 120 km has been so chosen as to match the value of the species number density at 120 km. The assumed turbopause height is at 105 km for this constituent.

Distribution of atomic oxygen

A perusal of the data in the literature /37,38,39/ shows two things very clearly regarding this constituent. The first is that it follows very closely the Chapman distribution whose form is

$$[O] = [O]_m . \exp 1/2\ [1-(Z-Z_m)/SH - \exp\{(Z-Z_m)/SH\}] \quad \ldots(6)$$

where $[O]_m$ is the value of the peak concentration located at Z_m, and SH is the shape factor. Offerman et al /37/ have shown for a large number of experimental data that the above peak atomic oxygen concentration correlates with the total column density of atomic oxygen up to an altitude of 110 km. From their correlation plot we have inferred that the value for the shape factor should be 5. It may be mentioned that the value from /3/ shown in their Figure (somewhat away from the correlation relation) would require a shape factor of 5.5. Further the above body of data also indicates Z_m to be around 97 km, so we choose this value. Within the limits of the variability of the atomic oxygen as noted in the various experiments the above choices for SH and Z_m seem reasonable to describe the variation of the atomic oxygen between 86 and 120 km.

Distribution of molecular Oxygen, Argon and Helium

These are calculated by choosing suitable values for the various a_i in Eqn (1) so that their concentrations match with the MSIS-83 model values at 120 km. The assumed levels of the turbopause for these species are respectively 105, 105 and 95 km as in the MSIS-83 model. With a given value of the concentration at 120 km it has been noticed by us that any choice of the turbopause height for the first two species between 95 and 105 km does not substantially affect their distribution between 86 and 120 km. But for helium which is very light it seems more appropriate to use the lower value namely 95 km for getting a suitable description. Figure 3 shows the distribution of the various species in ITRA from 80 to 120 km.

Mean sea level pressure

As discussed in the earlier paper /7/ a sea level pressure of 1010 mb has been chosen based on the southern and northern hemisphere tropical data from /40/ for the years 1951 to 1960 for nearly 200 stations. This value of the sea level pressure is somewhat lower than the mid-latitude value of 1013.25 mb in ISA.

Acceleration due to gravity (g)

For this we suggest a value corresponding to the Tropic of Cancer, which from Lambert's formula in /41/ is 9.78852 ms^{-2} (truncated to five decimal places).

TABLE 2: DEFINING PARAMETERS AND CONSTANTS FOR THE PROPOSED ITRA

Geop Alt (km)	0	6	16	46	51	74	84.69
Temp (^oC)	27(6.0)-9(6.5)-74(-2.3)-5(0.0)-5(3.0)-74(0.6)-80.40						
Geom Alt(km)	86	97	110	120	1000		
Temp (^oC)	-80.4 (0.6) -87 * -45 (-15) 105 ** 760						

The bracketed quantities denote lapse rate in ^oC/km. The (*) denotes an elliptical variation of temperature distribution, commencing with zero gradient at 97 km and ending with a gradient of 15^oC/km at 110 km, and (**) indicates a Bates type of profile commencing with a gradient of 15^oC/km at 120 km and ending with 1000 km.

Sea level pressure = 1010 mb ;

Acceleration due to gravity = 9.78852 ms^{-2}

Constituent	N_2	O	O_2	Ar	He
z_{ti}	105.0	-	105.0	105.0	95.0
$n(120)/m^3$	3.261+17	8.80+16	2.90+16	1.10+15	2.40+13

The molecular weight, the ratio of the specific heats of air, the gas constant, and the other constants for the transport properties are assumed to be the same as in /3/. The atmospheric properties for the proposed ITRA are provided in an abridged form in Tables 3 to 6.

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TABLE 1: KINETIC TEMPERATURE DATA IN ^{o}K CONSIDERED FOR PROPOSING ITRA

STATION / MODEL SATELLITE	LAT	LONG	PERIOD	DATA TYPE	ALT IN KM 50	55	60	65	70	75	80	85	90	95	100	Z/H	REF NO
Kwajalein	9 N	168 W	1956-78	S	270	261	246	230	213	200	196	194	191	186	179	Z	14
Asc & Natal	8 S		1960-70	G	267	261	248	228	211	201	197	200	189	185		Z	23
Thumba	9 N	77 E	1971-77	T	269	256	242	227	213	205	193					Z	19
Woomera	31 S	137 E	1957-63	S	267	259	249	232	218	204	191					Z	24
Wallops Is	38 N	75 W	1960-70	G		258	245	231	217	208	198	194	193	169	180	Z	23
Churchill	59 N	94 W	1960-70	G		258	251	236	226	216	201	193	194	194		Z	23
Cole & Kantor	Avg of 0 - 30 N			TPS	270	261	246	230	213	201	198	197				H	14
Koshelkov	Avg of 0 - 30 S			TPS	268	260	247	231	214	203	197					H	15
Cole & Kantor	45 N			TPS	269	259	246	234	222	211	202	194				H	14
Koshelkov	Avg of 40 S - 50 S			TPS		255	242	229	215	203	195					H	15
Asc & Natal	8 S		1960-70	P		261	248	237	220	207	207	210	215	215	200	Z	23
Wallops Is	38 N	75 W	1960-70	P		258	245	230	216	208	209	204	203	199	196	Z	23
Churchill	59 N	94 W	1960-70	P		241	239	236	228	213	213	207	199	203	205	Z	23
Alt in km	-->				52.7	56.5	60.1	63.5	66.7	70.0	73.1	76.1	79.1	82.2			
Nimbus	Avg of 30 S - 30 N			R	262	251	241	230	220	213	212	208	206	205		H	27
Nimbus	Avg of 45 S & 45 N			R	259	249	240	232	226	220	215	209	204	199		H	27
MSIS-83 data: $A_p = 4.0; F_{10.7} = 150$				Alt(km)		85	90	95	100	105	110	115	120				
	Avg of 30 S - 30 N					199	187	185	187	196	228	300	379			Z	30
	Avg of 45 N & 45 S					195	181	178	185	206	243	303	376			Z	30

T = Thermistor; G = Grenade; S = Sphere; P = Pitot; R = Radiance; H = Geopotential; Z = Geometrical

TABLE 3: ATMOSPHERIC PROPERTIES OF ITRA (SI UNITS)

GEOPT ALT (m)	PRES ALT (m)	TEMP (°K)	PRESSURE (mb)	PRESSURE RATIO	DENSITY (kg/m^3)	DENSITY RATIO	SONIC VELCTY (m/s)	UNIT REY NUMBER (s/m^2)
-2000	-1890	312.15	1.262 3	1.250 0	1.408 0	1.202 0	354.18	7.402 0
00	30	300.15	1.010 3	1.000 0	1.172 0	1.000 0	347.31	6.348 0
2000	1940	288.15	8.010 2	7.930-1	9.684-1	8.261-1	340.29	5.412 0
4000	3840	276.15	6.290 2	6.227-1	7.934-1	6.769-1	333.13	4.584 0
6000	5740	264.15	4.886 2	4.838-1	6.444-1	5.497-1	325.81	3.856 0
8000	7640	251.15	3.750 2	3.712-1	5.201-1	4.437-1	317.70	3.240 0
10000	9540	238.15	2.837 2	2.809-1	4.150-1	3.540-1	309.36	2.700 0
12000	11430	225.15	2.113 2	2.093-1	3.270-1	2.790-1	300.80	2.228 0
14000	13410	212.15	1.547 2	1.532-1	2.540-1	2.167-1	291.99	1.819 0
16000	15520	199.15	1.110 2	1.099-1	1.942-1	1.657-1	282.90	1.467 0
18000	17660	203.75	7.914 1	7.836-2	1.353-1	1.154-1	286.15	1.002 0
20000	19760	208.35	5.684 1	5.628-2	9.503-2	8.107-2	289.36	6.908-1
22000	21820	212.95	4.112 1	4.071-2	6.726-2	5.738-2	292.54	4.800-1
24000	23860	217.55	2.995 1	2.965-2	4.796-2	4.091-2	295.68	3.362-1
26000	25870	222.15	2.196 1	2.175-2	3.444-2	2.938-2	298.79	2.373-1
28000	27860	226.75	1.621 1	1.605-2	2.490-2	2.124-2	301.87	1.686-1
30000	29820	231.35	1.203 1	1.192-2	1.812-2	1.546-2	304.92	1.207-1
32000	31770	235.95	8.988 0	8.899-3	1.327-2	1.132-2	307.93	8.697-2
34000	33700	240.55	6.750 0	6.683-3	9.776-3	8.339-3	310.92	6.307-2
36000	35640	245.15	5.097 0	5.047-3	7.244-3	6.179-3	313.88	4.602-2
38000	37590	249.75	3.869 0	3.831-3	5.397-3	4.604-3	316.81	3.378-2
40000	39550	254.35	2.952 0	2.923-3	4.043-3	3.449-3	319.71	2.494-2
42000	41510	258.95	2.263 0	2.241-3	3.045-3	2.597-3	322.59	1.851-2
44000	43480	263.55	1.743 0	1.726-3	2.304-3	1.966-3	325.44	1.381-2
46000	45460	268.15	1.349 0	1.335-3	1.752-3	1.495-3	328.27	1.036-2
48000	47470	268.15	1.046 0	1.035-3	1.359-3	1.159-3	328.27	8.034-3
50000	49480	268.15	8.110-1	8.030-4	1.054-3	8.988-4	328.27	6.230-3
52000	51500	265.15	6.284-1	6.222-4	8.256-4	7.043-4	326.43	4.926-3
54000	53530	259.15	4.845-1	4.797-4	6.512-4	5.556-4	322.72	3.957-3
56000	55560	253.15	3.712-1	3.675-4	5.108-4	4.358-4	318.96	3.162-3
58000	57600	247.15	2.826-1	2.798-4	3.984-4	3.398-4	315.16	2.514-3
60000	59630	241.15	2.137-1	2.116-4	3.088-4	2.634-4	311.31	1.988-3
62000	61680	235.15	1.605-1	1.589-4	2.378-4	2.029-4	307.41	1.563-3
64000	63720	229.15	1.197-1	1.185-4	1.819-4	1.552-4	303.46	1.221-3
66000	65770	223.15	8.850-2	8.762-5	1.382-4	1.179-4	299.46	9.482-4
68000	67820	217.15	6.492-2	6.428-5	1.042-4	8.885-5	295.41	7.312-4
70000	69880	211.15	4.721-2	4.675-5	7.790-5	6.645-5	291.30	5.599-4
72000	71940	205.15	3.402-2	3.369-5	5.777-5	4.929-5	287.13	4.255-4
74000	74030	199.15	2.428-2	2.404-5	4.247-5	3.623-5	282.90	3.208-4
76000	76100	197.95	1.722-2	1.705-5	3.031-5	2.585-5	282.05	2.301-4
78000	78150	196.75	1.219-2	1.207-5	2.158-5	1.841-5	281.19	1.647-4
80000	80170	195.55	8.609-3	8.524-6	1.534-5	1.308-5	280.33	1.177-4
82000	82160	194.35	6.068-3	6.008-6	1.088-5	9.278-6	279.47	8.391-5
84000	84120	193.15	4.267-3	4.225-6	7.697-6	6.566-6	278.61	5.969-5
84690	84790	192.73	3.776-3	3.738-6	6.824-6	5.822-6	278.31	5.303-5

TABLE 4: ATMOSPHERIC PROPERTIES OF ITRA (SI UNITS)

PRESSURE (mb)	GEOPT ALT (m)	NUMBER DENSITY (m^{-3})	MEAN PARTICLE SPEED (ms^{-1})	MEAN COLLSN FREQ (s^{-1})	MEAN FREE PATH (m)	DYNAMIC VISCTY kg/(m.s)	KINMATIC VISCTY (m^2/s)	THERMAL CONDVTY W/(m.K)
1.010 3	00	2.437 25	4.684 2	6.758 9	6.931-8	1.847-5	1.575-5	2.626-2
8.500 2	1500	2.114 25	4.614 2	5.774 9	7.990-8	1.804-5	1.774-5	2.556-2
7.000 2	3130	1.802 25	4.535 2	4.837 9	9.376-8	1.757-5	2.027-5	2.479-2
5.000 2	5820	1.366 25	4.403 2	3.559 9	1.237-7	1.677-5	2.553-5	2.350-2
3.000 2	9610	9.029 24	4.195 2	2.242 9	1.871-7	1.551-5	3.571-5	2.151-2
2.000 2	12360	6.502 24	4.036 2	1.553 9	2.598-7	1.455-5	4.653-5	2.002-2
1.500 2	14190	5.152 24	3.926 2	1.197 9	3.279-7	1.390-5	5.609-5	1.902-2
1.000 2	16610	3.612 24	3.829 2	8.186 8	4.678-7	1.332-5	7.666-5	1.814-2
5.000 1	20790	1.723 24	3.919 2	3.998 8	9.803-7	1.386-5	1.672-4	1.896-2
3.000 1	23990	9.990 23	3.988 2	2.358 8	1.691-6	1.426-5	2.969-4	1.958-2
2.000 1	26610	6.481 23	4.042 2	1.551 8	2.607-6	1.459-5	4.682-4	2.008-2
1.000 1	31260	3.092 23	4.138 2	7.574 7	5.464-6	1.517-5	1.020-3	2.098-2
5.000 0	36140	1.475 23	4.236 2	3.699 7	1.145-5	1.576-5	2.221-3	2.190-2
2.000 0	42940	5.548 22	4.369 2	1.435 7	3.045-5	1.656-5	6.206-3	2.317-2
1.000 0	48350	2.701 22	4.427 2	7.078 6	6.255-5	1.691-5	1.302-2	2.374-2
5.000-1	53760	1.394 22	4.358 2	3.596 6	1.212-4	1.650-5	2.461-2	2.307-2
2.000-1	60470	6.043 21	4.186 2	1.497 6	2.796-4	1.546-5	5.318-2	2.143-2
1.000-1	65200	3.212 21	4.061 2	7.719 5	5.261-4	1.470-5	9.518-2	2.025-2
5.000-2	69640	1.707 21	3.939 2	3.979 5	9.899-4	1.397-5	1.702-1	1.913-2
2.000-2	75130	7.300 20	3.809 2	1.646 5	2.314-3	1.320-5	3.759-1	1.796-2
1.000-2	79140	3.695 20	3.786 2	8.279 4	4.573-3	1.306-5	7.350-1	1.775-2
5.000-3	83100	1.870 20	3.763 2	4.165 4	9.034-3	1.292-5	1.437 0	1.755-2
3.776-3	84690	1.419 20	3.753 2	3.153 4	1.190-2	1.287-5	1.885 0	1.747-2

TABLE 5: VARIATION OF SPECIES CONCENTRATIONS (m^{-3}) WITH ALTITUDE

ALT (km)	TEMP (^{o}K)	NITROGEN	ATOMIC OXYGEN	MOLECULAR OXYGEN	ARGON	HELIUM
86.00	192.73	1.108 20	2.907 16	2.972 19	1.325 18	7.435 14
87.00	192.13	9.353 19	5.961 16	2.509 19	1.119 18	6.267 14
88.00	191.53	7.893 19	1.054 17	2.114 19	9.432 17	5.274 14
89.00	190.93	6.657 19	1.650 17	1.777 19	7.939 17	4.425 14
90.00	190.33	5.612 19	2.339 17	1.488 19	6.668 17	3.699 14
91.00	189.73	4.728 19	3.056 17	1.242 19	5.586 17	3.079 14
92.00	189.13	3.982 19	3.736 17	1.031 19	4.668 17	2.551 14
93.00	188.53	3.352 19	4.325 17	8.529 18	3.889 17	2.102 14
94.00	187.93	2.820 19	4.788 17	7.020 18	3.230 17	1.723 14
95.00	187.33	2.372 19	5.110 17	5.750 18	2.675 17	1.406 14
96.00	186.73	1.993 19	5.294 17	4.689 18	2.210 17	1.312 14
97.00	186.13	1.675 19	5.351 17	3.808 18	1.820 17	1.235 14
98.00	186.29	1.401 19	5.301 17	3.069 18	1.490 17	1.155 14
99.00	186.77	1.170 19	5.166 17	2.462 18	1.216 17	1.076 14
100.00	187.58	9.766 18	4.967 17	1.969 18	9.900 16	9.989 13
101.00	188.73	8.143 18	4.723 17	1.570 18	8.044 16	9.242 13
102.00	190.24	6.785 18	4.452 17	1.250 18	6.528 16	8.531 13
103.00	192.15	5.652 18	4.165 17	9.937 17	5.293 16	7.862 13
104.00	194.50	4.707 18	3.873 17	7.900 17	4.291 16	7.238 13
105.00	197.36	3.920 18	3.583 17	6.283 17	3.479 16	6.660 13
106.00	200.83	3.280 18	3.302 17	4.924 17	2.665 16	6.129 13
107.00	205.08	2.745 18	3.033 17	3.861 17	2.035 16	5.643 13
108.00	210.38	2.294 18	2.778 17	3.033 17	1.556 16	5.197 13
109.00	217.38	1.913 18	2.539 17	2.385 17	1.192 16	4.785 13
110.00	228.15	1.579 18	2.317 17	1.865 17	9.073 15	4.385 13
111.00	243.15	1.294 18	2.110 17	1.454 17	6.898 15	4.003 13
112.00	258.15	1.073 18	1.920 17	1.154 17	5.338 15	3.683 13
113.00	273.15	8.999 17	1.745 17	9.304 16	4.198 15	3.415 13
114.00	288.15	7.615 17	1.585 17	7.611 16	3.351 15	3.190 13
115.00	303.15	6.500 17	1.438 17	6.310 16	2.710 15	3.000 13
116.00	318.15	5.590 17	1.305 17	5.296 16	2.219 15	2.841 13
117.00	333.15	4.842 17	1.183 17	4.495 16	1.836 15	2.706 13
118.00	348.15	4.220 17	1.072 17	3.853 16	1.535 15	2.590 13
119.00	363.15	3.700 17	9.715 16	3.331 16	1.295 15	2.490 13
120.00	378.15	3.261 17	8.800 16	2.900 16	1.100 15	2.400 13
200.00	925.92	3.525 15	4.515 15	1.869 14	2.530 12	8.346 12
300.00	1021.28	1.459 14	7.023 14	4.988 12	2.812 10	5.063 12
400.00	1031.75	8.101 12	1.341 14	1.838 11	4.576 8	3.334 12
500.00	1032.97	4.995 11	2.731 13	7.626 9	8.613 6	2.238 12
600.00	1033.13	3.345 10	5.830 12	3.476 8	1.823 5	1.521 12
700.00	1033.15	2.420 9	1.301 12	1.731 7	4.308 3	1.045 12
800.00	1033.15	1.884 8	3.027 11	9.371 5	1.130 2	7.255 11
900.00	1033.15	1.574 7	7.332 10	5.500 4	3.280 0	5.089 11
1000.00	1033.15	1.407 6	1.846 10	3.487 3	1.048 -1	3.604 11

TABLE 6: ATMOSPHERIC PROPERTIES OF ITRA FROM 86 TO 1000 KM

ALT (km)	TEMP (^{o}K)	ACCN GRAV (ms^{-2})	PRES SCALE HT (km)	NUMBER DENSITY (m^{-3})	MEAN PARTCLE SPEED (ms^{-1})	MEAN COLL FREQ (s^{-1})	MEAN FREE PATH (m)	MEAN MOL WT
86.0	192.73	9.528	5.81	1.419 20	375.4	3.152 4	1.191-2	28.96
87.0	192.13	9.525	5.79	1.198 20	374.8	2.658 4	1.410-2	28.95
88.0	191.53	9.522	5.78	1.011 20	374.3	2.240 4	1.671-2	28.95
89.0	190.93	9.519	5.76	8.529 19	373.8	1.887 4	1.981-2	28.93
90.0	190.33	9.516	5.75	7.190 19	373.4	1.589 4	2.350-2	28.91
91.0	189.73	9.514	5.74	6.056 19	373.0	1.337 4	2.790-2	28.88
92.0	189.13	9.511	5.73	5.098 19	372.6	1.124 4	3.314-2	28.84
93.0	188.53	9.508	5.73	4.287 19	372.3	9.448 3	3.941-2	28.79
94.0	187.93	9.505	5.72	3.602 19	372.1	7.934 3	4.690-2	28.74
95.0	187.33	9.502	5.72	3.025 19	371.9	6.658 3	5.586-2	28.67
96.0	186.73	9.499	5.71	2.537 19	371.8	5.584 3	6.658-2	28.60
97.0	186.13	9.496	5.71	2.127 19	371.7	4.680 3	7.942-2	28.53
98.0	186.29	9.493	5.74	1.776 19	372.4	3.914 3	9.515-2	28.44
99.0	186.77	9.490	5.77	1.480 19	373.4	3.272 3	1.141-1	28.35
100.0	187.58	9.487	5.82	1.233 19	374.9	2.736 3	1.370-1	28.26
101.0	188.73	9.484	5.87	1.027 19	376.7	2.289 3	1.646-1	28.16
102.0	190.24	9.481	5.95	8.546 18	378.9	1.916 3	1.977-1	28.06
103.0	192.15	9.478	6.03	7.115 18	381.5	1.607 3	2.374-1	27.96
104.0	194.50	9.475	6.13	5.927 18	384.6	1.349 3	2.850-1	27.85
105.0	197.36	9.472	6.25	4.941 18	388.2	1.135 3	3.419-1	27.73
106.0	200.83	9.469	6.39	4.129 18	392.5	9.592 2	4.092-1	27.60
107.0	205.08	9.466	6.56	3.454 18	397.5	8.128 2	4.891-1	27.47
108.0	210.38	9.463	6.76	2.891 18	403.6	6.907 2	5.844-1	27.34
109.0	217.38	9.461	7.02	2.417 18	411.3	5.885 2	6.989-1	27.20
110.0	228.15	9.458	7.41	2.006 18	422.6	5.018 2	8.421-1	27.05
111.0	243.15	9.455	7.95	1.658 18	437.6	4.293 2	1.019 0	26.88
112.0	258.15	9.452	8.50	1.386 18	452.2	3.710 2	1.219 0	26.73
113.0	273.15	9.449	9.04	1.172 18	466.4	3.235 2	1.442 0	26.58
114.0	288.15	9.446	9.59	9.995 17	480.3	2.841 2	1.690 0	26.45
115.0	303.15	9.443	10.14	8.597 17	493.7	2.512 2	1.965 0	26.33
116.0	318.15	9.440	10.68	7.447 17	506.8	2.234 2	2.269 0	26.23
117.0	333.15	9.437	11.23	6.493 17	519.5	1.997 2	2.602 0	26.13
118.0	348.15	9.434	11.78	5.693 17	531.9	1.793 2	2.967 0	26.05
119.0	363.15	9.431	12.32	5.018 17	544.0	1.616 2	3.367 0	25.98
120.0	378.15	9.428	12.86	4.443 17	555.8	1.461 2	3.803 0	25.92
200.0	925.92	9.199	38.93	8.238 15	954.9	4.656 0	2.051 2	21.50
300.0	1021.28	8.924	52.67	8.583 14	1094.1	5.558-1	1.968 3	18.06
400.0	1031.75	8.661	60.34	1.458 14	1153.7	9.953-2	1.159 4	16.41
500.0	1032.97	8.410	66.70	3.005 13	1195.2	2.126-2	5.622 4	15.31
600.0	1033.13	8.170	77.40	7.384 12	1269.0	5.546-3	2.288 5	13.58
700.0	1033.15	7.939	101.37	2.348 12	1431.6	1.990-3	7.195 5	10.67
800.0	1033.15	7.718	147.65	1.028 12	1703.5	1.037-3	1.643 6	7.54
900.0	1033.15	7.507	207.53	5.822 11	1991.7	6.864-4	2.902 6	5.51
1000.0	1033.15	7.304	256.39	3.789 11	2183.7	4.897-4	4.459 6	4.59

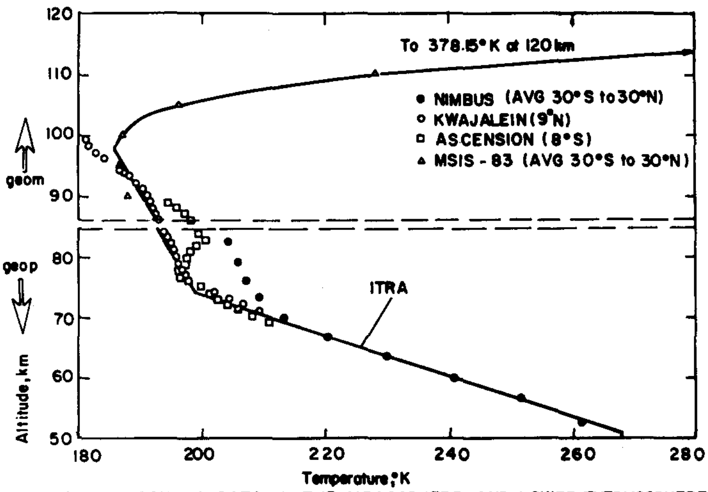

FIG. I COMPARISON OF DATA IN THE MESOSPHERE AND LOWER THERMOSPHERE WITH THE PROPOSED ITRA

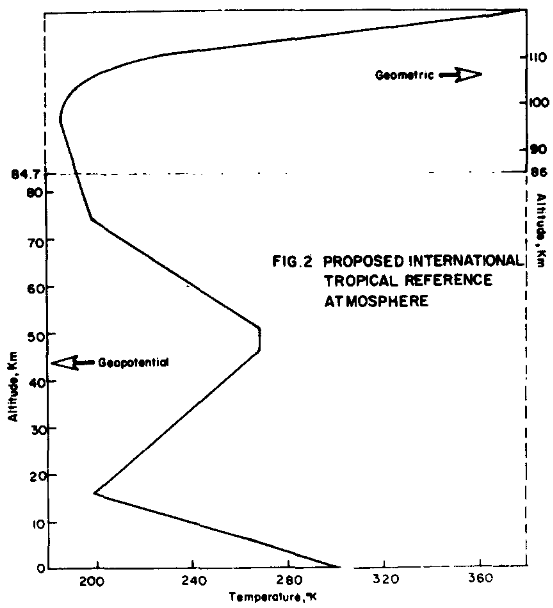

FIG. 2 PROPOSED INTERNATIONAL TROPICAL REFERENCE ATMOSPHERE

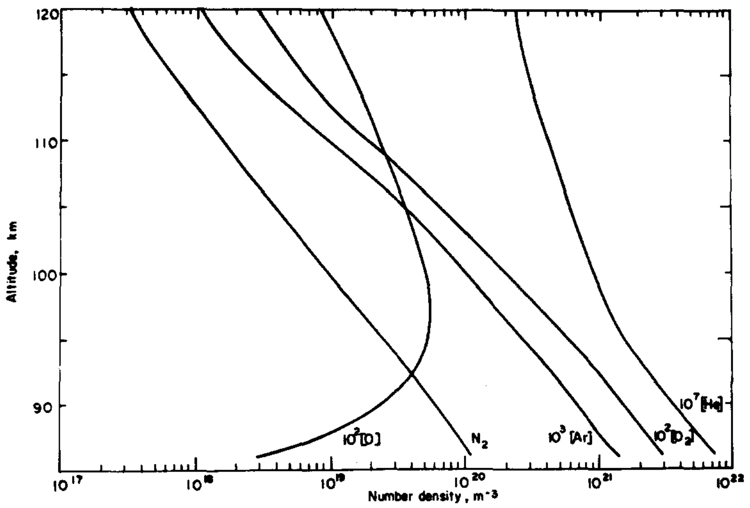

FIG. 3 VARIATION OF SPECIES CONCENTRATION IN ITRA